MINIATURE ROBOTS FOR SPACE AND MILITARY MISSIONS

C. R. Weisbin (JPL), J. Blitch (DARPA), D. Lavery (NASA),
E. Krotkov (Cytometrics, Inc.), C. Shoemaker (USARL),
L. Matthies (JPL), G. Rodriguez (JPL)

ABSTRACT

Miniature robots enable low-cost planetary surface exploration missions, and new military missions in urban terrain where small robots provide critical assistance to human operations. These space and military missions have many similar technological challenges. Robots can be deployed in environments where it may not be safe or affordable to send humans, or where robots can reduce the risk to humans. Small size is needed in urban terrain to make the robot easy to carry and deploy by military personnel. Technology to sense and perceive the environment, and to autonomously plan and execute navigation maneuvers and other remote tasks, is an important requirement for both planetary and surface robots and for urban terrain robotic assistants. Motivated by common technological needs and by a shared vision about the great technological potential, a strong, collaborative relationship exists between the NASA/JPL and DARPA technology development in miniaturized robotics. This paper describes the technologies under development, the applications where these technologies are relevant to both space and military missions, and the status of the most recent technology demonstrations in terrestrial scenarios.

INTRODUCTION

In recognition of the value of miniature robotics in enabling new and bold missions for surface exploration, the Jet Propulsion Laboratory (JPL), under support from the National Aeronautics and Space Administration (NASA), has for many years built and deployed a technology base in miniature robotics[1,2] . The Sojourner rover, deployed at Mars in the summer of 1997, emerged from this technology base. Beyond this, miniaturized robots currently under development will enable new capabilities in autonomous roving over long distances, deployment and operation of multiple science instruments, remote drilling and coring operations, and robotic selection and acquisition of samples for sample return missions. Similarly, DARPA has recognized the potential of miniature robotics technology, and has instituted major technology development programs to achieve technological breakthroughs in robot size, maneuverability, and real-time perception for navigation and reconnaissance. These activities are aggressively developing and demonstrating, in realistic urban terrain scenarios, such capabilities as carrying and deployment of a miniature robot by a single soldier, survival of impact due to being tossed over fences or other barriers, climbing stairs and other obstacles quickly, detailed survey and mapping of indoor and outdoor environments, and detection and localization of hostile forces.

A strong, collaborative relationship exists between the NASA/JPL and DARPA technology development in miniaturized robotics. This collaboration on miniature robotics began at a workshop on Military Robotics held at the Institute for Defense Analyses in May 1996. The authors of this paper were among the organizers of this workshop, and co-chaired a special session to identify critical needs and technologies in miniature robotics. This workshop was very successful in drawing wide participation from both the robotics research communities at academia and industry, as well as from the prospective user communities in the military. It also succeeded in providing an initial thrust toward establishing a new DARPA focus on miniature robot technologies for urban terrain, and to the initiation of the Tactical Mobile Robotics program[3] within the Tactical Technology Office (TTO) at DARPA. Since then, a large number of joint activities have taken place including workshops, coordination meetings, and even joint demonstrations where JPL and other robots have been tested in simulated military scenarios. As part of these efforts, JPL is currently leading a team of investigators from industry, universities, and government research laboratories, with the objective of enabling and demonstrating new capabilities in urban terrain operations. This paper will describe the miniaturized robotics technologies under development, the applications where these technologies are relevant to both space and military missions, and the status of the most recent technology demonstrations in terrestrial scenarios.

PLANETARY ROBOTICS TECHNOLOGY HIGHLIGHTS

Technological Requirements

An examination of the requirements for planetary robotics technology serves as a good starting point to discuss the role of this technology in a wide range of exciting planetary missions. For several key technologies, the desired capabilities, the state-of-the-art, and the technology requirements for emerging planetary missions is summarized below:

SURFACE MOBILITY: Planetary rovers are viewed as essential for long range planetary surface exploration missions, involving rover traverses of 10's and even 100's of kilometers. This requires navigation systems for long-range position determination and path control.[1,2] Such a requirement compares with the total mission traverse of 104 meters achieved by the Sojourner rover in its 1997 pioneering traverse on the Martian surface.

LONG OPERATING LIFE: Planetary robots must survive for long periods of time under the harsh environmental conditions of Mars and other planetary surfaces, in order to select and acquire the scientific data necessary to achieve quite challenging mission objectives. Objectives in the range of 100-1000 days are under consideration, without the use of thermal control using radioactive sources. [1,2]

ACQUIRE, HANDLE, PROCESS AND PACKAGE SAMPLES: Small rocks, soil specimens, and other scientific samples must be selected, acquired, and packaged in order to enable sample return missions currently under design.[1,2] This requires the use of lightweight manipulation systems, guided by vision and touch for grasping operations, that can achieve their function with a minimal amount of power, volume, and mass requirements. The state-of-the-art in robotic arm flight systems for planetary missions are the robotic arm deployed from the Viking lander in the 1970's, and a long-reach manipulator to be flown on the Mars Volatile and Climate Surveyor (MVACS) mission scheduled to be launched in late 1998.

EMPLACEMENT OF MULTIPLE SCIENCE INSTRUMENTS: Rovers equipped with multiple sensors for gathering of various types of scientific data (optical imaging, spectroscopy, etc.) are essential for planned missions to Mars and other objects in the Solar System. [1,2] Robots need to deploy and point or place these instruments next to selected rocks and other scientific samples of interest. These operations must be done autonomously in order to minimize the amount of time required for the instrument placement and science gathering operations, thereby maximizing the amount of scientific data that can be gathered in a given time period. The state-of-the-art in robotic flight systems for instrument placement maneuvers is again the Sojourner rover, which successfully took measurements at various sites in the vicinity of the Pathfinder lander, using an Alpha-Proton X-ray Spectrometer (APXS).

ROBOT AUTONOMY: Planetary robots must operate autonomously because of the long time that it takes to communicate with them from Earth.[1,2] Each command sent by ground controllers must result in the autonomous execution of relatively complex tasks such as moving over long distances, acquiring samples of interest, and taking scientific measurements at interesting locations. As the sequence of steps that the robot must take is executed, the robot must verify to itself that intermediate goals are satisfied in order to make sure that each step is correctly executed before proceeding to the next step. In cases where any given step is not completed successfully, the robot must move into a safe operational mode, or must take corrective action to compensate for the failure.

SAMPLE SELECTION AND SCIENCE GOAL IDENTIFICATION: Planetary robots must be capable of terrain-image analysis and object identification in order to recognize samples that could be of interest for further investigation. [1,2]

Sojourner: A Trail-Blazing Robot

The Sojourner rover, flown in the 1997 Mars Pathfinder mission, did more than find a path, and could actually be characterized as a trail-blazing robot. The rover has a mass of about 11 kg and is about the size of a child's small wagon. It has six wheels mounted on a rocker-bogie suspension chassis, and can move at speeds of about 0.6 meters per minute. This is not very fast, but the speed is appropriate because of the exploratory and relatively risky nature of its mission. The 6-wheel chassis provided substantial stability in going over rocks and other obstacles without tipping over. Motion sensors along the rover frame can detect excessive tilt and stop the rover before it gets dangerously close to tipping over. While its primary mission was to demonstrate that small rovers can actually operate on Mars, the rover went far beyond this and acquired a wealth of scientific data about the planet surface.[4] Its performance as a robotic system is summarized as:

Figure 1: Mars Pathfinder Rover – Sojourner

- It executed a total of 234 movements commanded from the ground, in the form of designated way-points that the rover followed in going from one place to another.

- It traversed a total of 104 meters over a period of about 30 days. It deployed the APXS sensor at 17 sites during this period.

- It took a total of 534 images from the rover cameras, and these images were used for rover navigation, and to see more closely certain features of the Martian surface that were far or occluded from the lander cameras.

- It conducted 2 complete and 23 short soil mechanics experiments to analyze topsoil compactness and density.

- It returned 245 Mb of data in the form of images, APXS scientific measurements, and engineering data from various types of on-board sensors.

This small, dependable vehicle proved that robotics can be an invaluable tool for scientific exploration of planetary surfaces. In addition to its resounding success of its mission operations, its major impact has been that robotic rovers are now baselined as a standard for all planned planetary surface exploration. The robotics technology currently under development to fulfill this promise is described in the next section.

SPACE TELEROBOTICS TECHNOLOGY

One of the primary objectives in space robotics is the development of miniaturized rovers for long range autonomous traverse on planetary surfaces, and for deployment of multiple science instruments. These rovers are being equipped with adaptively controlled micro-manipulators and drill mechanisms for smart soil and rock sample acquisition and inspection. In addition to rovers, types of robot of increasing interest are the robotic explorers for deep penetration and in-situ analysis of planetary sub-surfaces. The emphasis is on integrated robotic systems which offer a system-level functional capability to prospective users. A brief summary of each of these integrated robotic system prototypes follows.

Sample Retrieval Rover

This effort focuses on the issues of surface rendezvous, docking and sample transfer between two rovers or a rover and lander on the surface of Mars.[5,6,,7] The Sample Retrieval Rover (SRR) would retrieve, in as little as one diurnal cycle, previously acquired cached samples gathered by another rover, and that need to be returned to an Earth-return ascent vehicle. SRR has been simulated near-field operations (10 to 100 meters) about an ascent vehicle. The vehicle does local-area navigation to a known location, cache sample recognition and localization, robotic sample container pickup, and transport of the sample back to the ascent vehicle.[8,9,10,11]

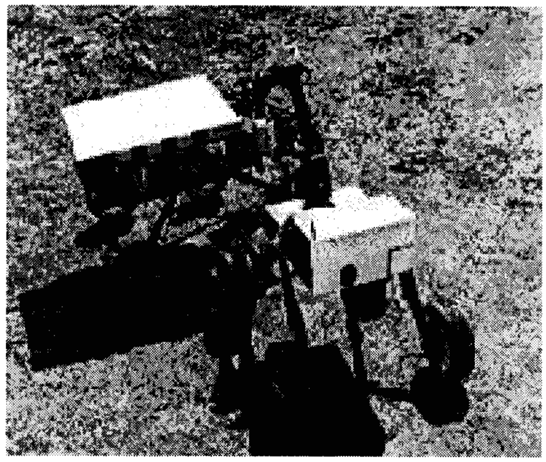

Figure 2: Sample Return Rover

The surface rendezvous, docking and sample transfer operation is highly autonomous once a direction to the target science rover cache has been established. The SRR moves under beacon-guidance to the near area, visually localizes the other rover in aspect and range, and plans a terminal trajectory. It then visually acquires an accurate position of the cache (sample repository), and executes visually-referenced inverse kinematics control of a small, strong, all-composite, robotic arm to transfer selected samples onto the SRR platform.

The SRR vehicle incorporates a number of novel architectural features, among them are fully collapsible running gear and wheels enabling it to stow in about 1/3 its operating volume. Prior to the sample transfer operation, the rover positions itself for ground clearance and to be best configured to the task at hand.

Long Range Science Rover

Long-range science rovers are those that would enable 10-to-50 kilometer traverses in support of Mars rover sample-selection and sample-return missions. Enabling technologies include: long-distance, non-line-of-sight navigation[12, 13]; survivability of systems operating in severe diurnal cycles and harsh terrain; efficiently stowed vehicles (e.g., collapsible wheels) that can expand in volume upon arrival at their destination; autonomous confirmation of goals and concatenation of commands. In addition, the rover must communicate via an orbiter to Earth, catalog and cache samples for later collection and return, and deployment and in situ analysis of data from multiple instruments.

A prototype, designated as Rocky 7, has navigated successfully over a corner of Lavic Lake, an ancient lakebed about 280 kilometers east of Los Angeles, California, and has taken panoramic photographs and close-ups of the cratered terrain in two field tests[14]. In the most recent test, a ~1-kilometer desert traverse was completed, including several site surveys, each consisting of performing experiments on several rocks[15]. During this tests, simulated descent images taken by a helicopter were used by the science team and the rover operator to determine where to send the rover and to interpret the rover location. Science instruments (a Mossbauer spectrometer and a nuclear resonance magnetometer spectrometer) were used to conduct science experiments on rocks in addition to the infrared spectrometer carried by the rover.

Dexterous Manipulators

This task develops small, dexterous arms for rover science and sample return [6,16]. Earlier work developed a lander robotic arm concept for the Mars Volatiles and Climate Surveyor (MVACS) mission to be launched in late 1998. The robotic science operations under investigation are diverse and require coordinated advances in robot mechanization and sensor-based intelligent robotic control for remote unstructured, uncertain environments. Control challenges include synthesis of autonomous robotic behaviors that embed basic manual skills of a field geologist, task-adaptive contact interactions with highly variable media, visually guided positioning and placement of instruments, probes, and sampling heads, and generation of 3-D sensing techniques.

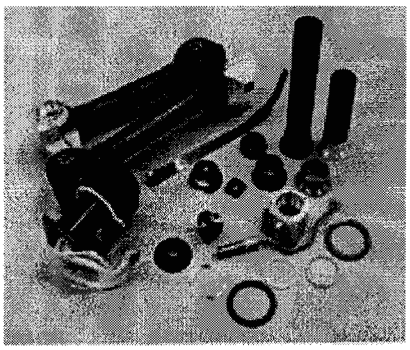

Figure 3: Components of Micro-arm for Sample Acquisition from Rover Platform

Science requirements include dexterous robotic operations for viewing; analytic probing; instrument emplacement; material extraction and preparation; sample exposure, acquisition, manipulation, and containment; and visual localization and pickup of a stored sample cache for transfer to an ascent vehicle and return to Earth.

Segmented-Drill Robotic System

This task develops the enabling technologies for an automated deep drilling and sampling system using a segmented-stem drilling mechanism. The mechanism can perform autonomous rock coring, a key operation for planetary and small body missions.

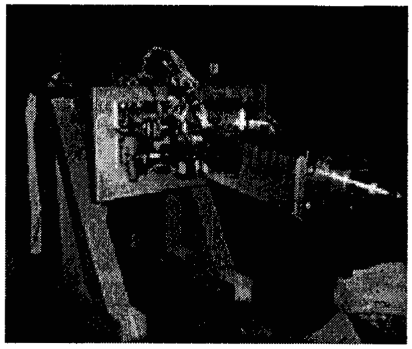

Figure 4: Miniature Robotic Device for Coring of Rock Samples

These missions require the acquisition of subsurface samples by drilling, followed by sealing and containerization of the sample. Sealing and containerization protects the samples during multiple transports across separation and docking interfaces. A solution to the problem of acceptably sealing a sample container, and insuring that the sample return container meets planetary protection requirements, will be relevant to both Mars and cometary sample return missions. Drilling and sampling to depths greater than that previously demonstrated is highly desirable to planetary scientists as well.

Subsurface Explorer

An alternative approach to deep drilling is embedded in what is referred to as a Subsurface Explorer, a stem-less robotic vehicle capable of maneuvering in the expected regolith (e.g., soil, permafrost) of planets, such as Mars, and small bodies, such as comets. This system penetrates to depths of meters, to hundreds or even thousands of meters (depending on material properties) and makes in situ measurements of soil composition and chemistry. Longer-term development will involve subsurface exploration techniques to depths of tens and hundreds of meters for both lander-based and roving systems, and vehicles for penetrating ice layers (100 to 10,000 meters) and moving through potential underground bodies of water.

The goal of the prototype development effort is to construct a self-contained vehicle that can reach depths much greater than those achievable with any reasonable-mass traditional drill rig attached to a surface lander.

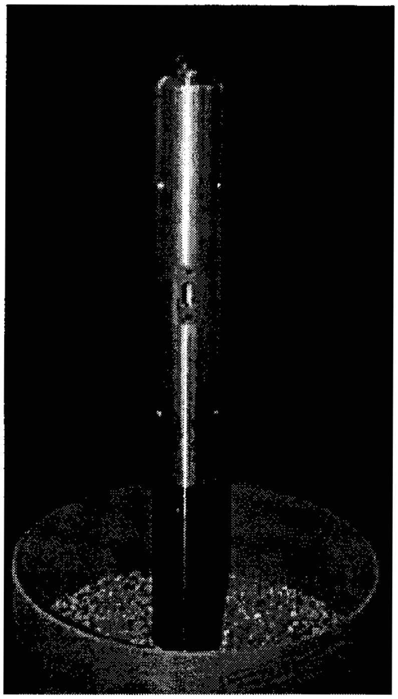

Figure 5: Subsurface Explorer Robot

The body of the prototype vehicle is ~1 meter long and ~5 centimeters in diameter. The front half of the vehicle contains a percussive hammer mechanism. A closed gas system will compress the working gas and then rapidly release it into the hammer chamber, propelling the hammer into the anvil or body of the vehicle with very high energy. Material selection for components of the explorer vehicle is critical to ensure strength, durability, and wear resistance as the hammering action encounters the surrounding surface and subsurface material. The impact of the hammer will overcome the frictional forces on the vehicleÕs outside surface caused by the surrounding material, and will force away material from the nose of the vehicle, moving it forward. The science package of in situ instruments is located behind the percussive mechanism.

The package is spring mounted to prevent damage caused by the high impacts of the hammering. Instruments being explored include microscopic imaging and laser Raman spectroscopy of material against the body of the vehicle, which can be done via a sapphire window in the wall. Behind the science package are the control and communication avionics and tether deployment mechanism. A very thin tether, deployed from the vehicle, provides both power (high voltage) and communication to and from the lander. The tether is effectively buried behind the vehicle as it goes.

Nanorover Technology

The nanorover task is a technology-development effort to create very small (10 to 100 grams), scientifically capable robotic vehicles that can easily fit within the mass and volume constraints of future asteroid, comet, and Mars missions. Important technology elements of this task include: miniaturization of all rover systems, including science payload; and computer and electronics design for operation without thermal enclosures and control to survive ambient temperature ranges of -125 to +125 Celsius. The technology also includes miniature actuator usage and control in thermal/vacuum environments; mobility and navigation in low-gravity (1/100,000 that of Earth) environments; and sensing and autonomous control of rover operations.

Figure 6: Self-Righting Nanorover Vehicle

The current nanorover prototype shown in the figure consists of a four-wheel mobility chassis designed so that each wheel strut can be positioned independently. The nanorover can pose its body in any orientation to perform various tasks; for example, pointing science instruments at features of interest. Each aluminum wheel of about 6 centimeters in diameter contains a drive motor and helical cleats on the outside to increase performance for skid steering while turning in place. The chassis is designed around two science instruments: a multi-band camera system for gathering images, and a near-infrared point reflectance spectrometer (1 to 2.5 micrometers) to provide mineralogical information. The onboard computer is designed around radiation-hardened components. The nanorover is designed to be completely solar powered, requiring only 1 watt, including an RF telecommunications system for communications between the rover and a lander or small-body orbiter for relay to Earth. The power source is 500 grams of commercial, non-rechargeable, replaceable lithium batteries, with energy density of 750 joules per gram.

The nanorover operates upside-down, intentionally flips over, and recovers from accidental overturning. It places its body flat on the ground for sensor placement, runs low to the ground on severe slopes or under barriers, rises up on struts for the highest possible vantage point and stair climbing. It lifts wheels and sets them atop obstacles, and articulates to keep all wheels providing maximum traction. The vehicle incorporates ultra-low-power active pixel sensing, CMOS imaging technology, ultra-low-noise analog input for advanced sensing (e.g., thermal infrared), and ultra-low-mass commercial RF digital communications.

Specifications for the current prototype are 2 kilograms mass and width of 28 centimeters. In the stowed configuration, the vehicle is 28 centimeters long and 7 centimeters high. In the operational configuration, it is 25 centimeters high. Run time (fully charged battery) is 35 hours, while operating cameras and sending data. It moves at 1 meter per second at maximum speed for a total of 5 hours. The maximum height of the traversable step is 20 centimeters. The maximum width of a traversable ditch is 20 centimeters. The maximum traversable slope is 50 degrees.

The nanorover has been selected as a technology experiment on the Japanese asteroid sample-return mission MUSES-C, scheduled for launch in January 2002. For this mission, the nanorover will be deployed to the asteroid surface to gather close-up imagery and spectral data, then relay the data through the MUSES-C spacecraft back to Earth.

TACTICAL MOBILE ROBOTICS

The DARPA Tactical Mobile Robotics program[3] is developing mobile robotic technologies to enable land forces to dominate the battle-space using teams of mobile robots in complex terrain (urban, indoor, rugged). The program provides the potential for intelligent, cooperative platforms integrated with a large variety of payloads for missions that take place in inaccessible or highly dangerous environments, concentrating particularly on urban environments.

Technical Requirements and Objectives

Specific robotic technologies being advanced include perception, autonomous operation, and locomotion. Envisioned perception capabilities include: (a) an on-board multi-sensor perception system capable of detecting at least 80 percent of decimeter-scale terrain hazards and at least 95 percent of meter-scale terrain hazards, both at 20 Hz, and (b) multi-source mapping algorithms capable of creating topological maps of urban structures with 90% accuracy. Autonomous operation capabilities will include: (a) coordination of the tactical behavior of a 10-robot team with 10X fewer command cycles, and (b) traversal of rugged/complex terrain using 1 command per 100 m travel. Locomotion capabilities will feature sub-meter-scale vehicles traveling at up to 1 m/s over 25 cm steps and decimeter-scale rubble. In addition to movement on the surface, the locomotion goals of some of the robot concepts under development include digging or burrowing about 0.5 meter through soil, while maintaining quiet and power-efficient operations. Other concepts call for climbing of high (up to 10 meters) walls, and for land & self-right after a 100 meter drop from the air.

The approach being used for technology development is to first develop advanced concepts of operation for tactical mobile robotics in urban missions, followed by demonstration of tasking and control of multiple robotic vehicles from single workstation. At the same time, technology development is under way in the areas of robot perception, autonomy, and locomotion. These technology developments will be embedded into complete designs of integrated systems. Once the systems are integrated, the concepts will be refined for operation for tactical mobile robotics in urban missions. Breadboards for demonstration of robot perception, autonomy, and locomotion capabilities in urban scenarios are being developed. Finally, competing designs for integrated system will be evaluated.

These activities build upon the prior results of the Demo II and the on-going Demo III DARPA programs to demonstrate the value of robotics technology to military operations, with a focus on autonomous vehicles. The goals of the Demo III program are to conduct a set of demonstrations of up to 40 mph when traveling on roads, going up to 20 mph in cross country in daytime under dry conditions, and 10 mph at night under wet conditions. The vehicle must detect and avoid all obstacle autonomously. Within this program, researchers at JPL are developing technology for real-time stereo vision for day and night navigation and real-time terrain classification. Obstacle detection is done using both range and classification information. Related capabilities also under development at JPL for the Demo III program are gaze control and terrain-adaptive velocity control based on visual look-ahead and vehicle dynamics.

In the Tactical Mobile Robotics program, the thrust is toward substantial decreases in size and increases in autonomy when compared to the earlier Demo III demonstrations, while at the same time achieving coordinated operation of multiple, distributed robotic systems working together to achieve a prescribed mission.

For the purpose of illustration of the systems under development within the Tactical Mobile Robotics initiative, a more detailed description of one of the many tasks within this initiative is set forth in the following section.

AN URBAN ROBOTICS DEMONSTRATION ACTIVITY

Under sponsorship from DARPA, a team formed by researchers from the Jet Propulsion Laboratory, IS Robotics, Inc., Carnegie-Mellon University, Oak Ridge National Laboratory, and the University of Southern California is engaged in a cooperative technology development activity to produce and demonstrate a prototype miniaturized robot for indoor and outdoor reconnaissance and building clearance. The activity is intended to demonstrate the miniature robot technology in a set of two simulated operational scenarios:

- AUTONOMOUS STREET CROSSING & OPEN DOORWAY ENTERING: A soldier deploys a small robot in the vicinity of a building, and designates by line-of-sight the goal for the robot, using the imagery emerging from the robot cameras to implement this designation. The goal consists of crossing a street and entering an open doorway. In response to this goal, the robot traverses the street autonomously goes through door, sending back reconnaissance imagery to the soldier.

- AUTONOMOUS STAIRWELL ASCENT: The soldier designates the goal to go up a stairwell that has been located from the robot imagery. The robot responds to this command by executing the stairwell ascent maneuver autonomously.

These two demonstrations will establish the foundation to proceed toward the following more ambitious and challenging demonstration:

- LONG OUTDOORS TRAVERSE FOLLOWED BY IN-DEPTH INDOORS MAPPING AND RECONNAISSANCE: The miniature robot is deployed at a long distance away from the entrance to a building whose indoors need to be explored. The outdoors terrain is difficult, in the sense that it contains challenging natural slopes and other obstacles, and possibly human-made barriers and other obstacles intended to impede movement in the vicinity of the building. A map is available of the outdoor terrain. The soldier initiates the operation by non-line-of-sight designation of the goal. The robot responds to this goal by autonomously traversing toward it. Once there, the robot enters the building and conducts a detailed mapping and exploration mission. The robot continually transmits reconnaissance information back to the operator. The initial focus is on daylight operation, but the option for subsequent operations under night or low-light conditions.

These demonstrations will highlight the following operational functions:

- High mobility – ability to climb curbs and stairs, scramble over rubble, and go through grass at speeds > 1 m/s, while at the same time detecting and avoiding obstacles.

- Autonomous position estimation and terminal guidance, both outdoors and indoors, without requiring GPS.

- Indoor mapping and exploration

- Goal designation in imagery or with map-based planning, or using both images and maps in combination.

- Non-line-of-sight communication that can support sending images back from the vehicle

- Hand-held, easy-to-use operator control unit.

- Several modes of control including teleoperation, waypoint designation, and autonomous navigation.

A miniature robot intended to accomplish these objectives is currently under development and evaluation. The mobility platform consists of an articulate track urban robot developed by IS Robotics. The mobility or locomotion platform is equipped with such embedded low-level behaviors as scrambling, reactive obstacle avoidance, and wall-following.

Figure 7: ISX Robot Platform developed under DARPA contract by IS Robotics, Inc.
(Image courtesy of IS Robotics, Inc.)

A two-processor architecture achieves a partitioning between the low-level control functions necessary for reactive behaviors, and the high-level perception and planning necessary for robot autonomy. Obstacle detection and avoidance is achieved with a forward-looking stereo pair, a single-axis scanning laser rangefinder, as well as sonar and IR proximity sensors. A panoramic camera is used for situation awareness, mission designation, and reconnaissance. A wireless local-area network or a single point-to-point communication channel is used to transmit commands to the robot and to return images and other data from the robot to the operator. Finally, a hand-held operator control with a touch screen is used to command the robot from a remote site. The key technologies that enable the robot operations outlined above are:

- A highly capable tracked mobility platform that has small mass and volume, climbs stairs and turns quickly, goes over obstacles rapidly, and carries relative large payloads in the same range as the robot own weight. The platform also operates for long periods at a reasonable power usage, and has built-in reactive behaviors for wall-following and other similar low-level tasks.

- Position estimation based on fused multi-sensor data to determine where the robot is with respect to objects in its local environment and with respect to more global building-map coordinates. Data from the stereo cameras, the scanning laser range sensor, and other sensors is combined with an analytical model of the robot movement and with speed and direction data coming from internal sensors such as motor encoders.

- Obstacle detection and avoidance sensors and algorithms to detect objects in the robot outdoors and indoors environment, and to conduct avoidance maneuvers when necessary.

- Omni-directional imaging, visual servoing, waypoint driving, and outdoor map-based planning to enable a variety of driving modes for the robot, while providing robustness to rough motion and error recovery with minimal user intervention.

- Robust, high-velocity indoor mapping for planning of paths and maneuvers and to guide the indoor exploration mission of the miniature robot. The goal is to develop indoor annotated maps, while driving at speeds greater than 1 m/sec, while operating in the two distinct modes of designated way-point navigation and autonomous exploration.

- A hand-held operator control unit that is small and lightweight, needs no or minimal textual entries, requires minimal training time, is touch sensitive, and interferes minimally with the operator awareness. The operator control unit is intended to achieve a high-level of situational awareness with minimal training and set-up.

COMPARISON OF SPACE AND TACTICAL MOBILE ROBOTICS REQUIREMENTS AND TECHNOLOGIES

The space and tactical mobile robotics technologies[1,2,3] have many areas of common interest, some of which have been discussed in the previous sections. There are also substantial differences. Both similarities and differences are summarized in the following table.

Illustrative Goals for Miniature Robots

Features	Space Robots	Urban Robots
Length (cm)	< 100	< 80
Width (cm)	< 140	< 50
Height (cm)	< 50	< 20
Robot Mass (kg)	1 to 60	< 10
Mission Life	90 to 300 days	1 to 10 days
Speed (cm/sec)	2 to 10	> 100
Mobility	Rocky terrain	Stairs, walls, etc.
Meters/command	10 to 100	10 to 100
Remoteness	Inter-planet	Local-area
Sampling	Get soil/rocks	Get objects

In terms of size and mass, space and urban terrain robotics have a very similar overarching objective: make the robots as small as possible, while still retaining the ability to do useful work. Power requirements are somewhat similar in terms of power levels needed, but there are significant differences. In space, since there is no direct access to the robot, solar power is critical and batteries cannot be exchanged as they can in terrestrial applications. Space robots must survive extreme temperature cycles, a constraint not typically needed for urban robotic systems. They must also survive without direct maintenance and attendance for extremely long periods in the order of several months and possibly more.

Speed and mobility requirements are to some extent similar, but there are also important differences. Urban terrain robots must climb stairs, go over rubble, and exhibit "scrambling" behavior when conducting time-limited military operations. On the other hand, while speed is also important for planetary robotics in order to maximize the science acquired over a fixed time period, the requirements are not typically as severe.

The distance between the robot and the human operator is much larger in the case of space robotics. This has profound implications about the extent of autonomous fault-protection and recovery strategies that must be embedded into the space robot on-board computer control system, as there is no means for a human to directly act on the robot to prevent failures, and to recover from them when failures occur.

However, in spite of the differences in several critical areas, there is a substantial range of technologies in which the requirements and objectives of space and military robotics are common. It is in these commonly important areas that the collaboration described in this paper is yielding its most substantial benefits, as outlined in the following section.

A CASE FOR THE NASA/AIAA PARTNERSHIP PRIZE

The collaboration in robotics technology development between space robotics and military robotics occurs at multiple levels in a technical and programmatic hierarchy, which can be illustrated by a simple 2-tier architecture as shown in the figure.

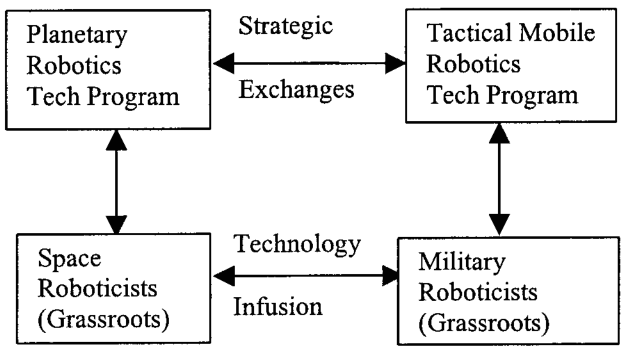

Figure 8: Two-Tier Architecture for Strategic Exchange and Technology Infusion

The upper level in the hierarchy illustrates the communication, exchange and coordination that exists at programmatic levels. This level, which represents the activities in which program leadership is engaged, sets the overall framework and environment for more detailed technical collaboration that occurs at the lower level in the hierarchy. In other words, program leadership on both sides, space and military, is providing the necessary climate for technologists to work together and infuse their technologies into space and military tasks. In the upper level, joint workshops, coordination meetings and planning strategies are held among several of the authors of this paper. These activities result in the definition and coordination of new thrusts and initiatives. At the lower level, technologists are engaged in detailed interactions leading to specific tasks. Specific recent results of this 2-level collaborative process is summarized below:

- At the grassroots engineer level, there is substantial commonality between the technologies being developed for space and those being developed for military applications. A prime example of this is the work that for many years in which researchers in machine vision at the Jet Propulsion Laboratory have conducted in collaboration with military personnel at the US ARMY Research Laboratory, joining forces in order to develop and demonstrate robotics technology for the DARPA Demo II and Demo III programs.

- Similar activities at the grass-roots level have led to the use of technology in vision-based obstacle avoidance developed for military programs being used in NASA missions, starting with Sojourner and continuing with rover-based planetary mission planned over the next decade. A complementary path for technology infusion is being achieved in the opposite direction, in that space-targeted technology for obstacle avoidance and navigation is finding its way into military activities in urban terrain robotic operations.

- The DARPA-funded program in urban terrain tactical robotics, in which robotics researchers at JPL are leading a multi-institutional team with participation from major centers for robotics research at CMU, USC, IS Robotics, and the Oak Ridge National Laboratory, is providing a framework for opening a uniquely new application of miniature robotics technology to urban terrain military operations.

- There are frequent exchanges and sharing of plans, in preparing and advocating new initiatives and thrust areas of benefit to both space and military domains. For example, the workshop co-organized by several of the authors of this paper and held at the Institute of Defense Analyses in May 1996, provided the initial framework to begin advocacy of the military research initiative leading to the DARPA program recently instituted in urban terrain robotics. Similarly, a workshop on military robotics was held at JPL in February 1997 to explore the applications of robotics technology into the 21st century.

- The military and space thrusts in miniature robotics are mutually invigorating and re-enforce their strength and projected applications. Success in instituting the recently established DARPA initiative in miniature military robotics, to some extent motivated by Sojourner and other planetary robotics technology, has led to an re-invigoration of the space robotics thrust toward miniaturization and low cost, mass, and volume intelligent robotic systems.

Military and space robotics are independently funded by their respective, responsible agencies. Together, they constitute a major force toward the development of highly advanced technologies in miniature robotic systems. Many of the technologies under development in both programs are concurrently useful to both military and space applications. That there is no official agreement of partnership allows a beneficial amount of flexibility in the scope, content, and timing of the collaborative activities. The collaboration effectively functions as a partnership. Opportunities for technical exchange and infusion are easily capitalized on by individual researchers in pursuit of their technologies, operating under the enlightened leadership at the institutions involved. The program leaders provide the enlightened framework and advocacy, while the grass-roots researchers implement specific tasks in technology development and 2-way technology transfer. Technology infusion is being achieved by having the individual researchers transfer the knowledge gained in developing technology for space into military applications, and by also implementing the reverse process from military tasks into the space domain.

One of the major achievements that a partnership can make is to advance the common good, while at the same time providing the framework for involved personnel at the participating institutions to flourish in their areas of technical excellence. To a large extent, the activities outlined in this paper are achieving this, while at the same time developing the technological breakthroughs needed to enable the widespread application of miniature robotics in urban terrain and space robotics missions.

Proposed Use of the Partnership Prize

A grand-challenge robotic design competition, targeted at high-school science students, will be established to develop concepts and prototypes for the most innovative possible "pocket-size" robot capable of doing useful work after being deployed from a small enclosure. The goal is to involve young and intensely creative students and budding researchers in the unique endeavor of creating the next generation of small robot systems concurrently useful to in space and on Earth. This competition will be held under the auspices of a an academically accredited institution and a technical society with interest in robotics and engineering for space and military applications. Winning bids for the competition will result in a 4-year scholarship being awarded for attendance of a college chosen by the winning participant.

ACKNOWLEDGEMENTS

The outstanding contributions of the multi-institutional team involved in the tactical mobile robotics for urban terrain operations technology development task described in this paper are acknowledged: Dr. L. Matthies of the Machine Vision and Tracking Sensors Group at the Jet Propulsion Laboratory; Drs. L. E. Parker, N. Rao, and C. Touzet of the Center for Engineering Science Advanced Research at the Oak Ridge National Laboratory; Professors G. Bekey and G. Sukhatme of the Robotics Research Laboratory at the University of Southern California; Dr. H. Greiner of IS Robotics, Inc.; and Drs. M. Hebert, A. Stentz and C. Thorpe of Robotics Institute at Carnegie-Mellon University. The authors also express their appreciation to Dr. C. Won of IS Robotics Inc., for granting permission to use the ISX Urban Robot mobility platform image and to make reference to the platform in the text of this paper.

The JPL research described in this paper was performed at the Jet Propulsion Laboratory of the California Institute of Technology, and was partially supported by the National Aeronautics and Space Administration (NASA) and by the Defense Advanced Research Program Agency (DARPA).

ABOUT THE AUTHORS

Charles R. Weisbin, Manager
Robotics and Mars Exploration Technology Programs
Jet Propulsion Laboratory

Lieutenant Colonel John Blitch, Manager
Tactical Mobile Robotics Program
DARPA Tactical Technology Office

Dave Lavery, Program Executive
Telerobotics Technology Program
NASA Office of Space Science

Erik Krotkov, President
Cytometrics, Inc., Philadelphia, PA 19106

Charles Shoemaker
Robotics Program Manager
US Army Research Laboratory

Larry Matthies, Supervisor
Machine Vision and Tracking Sensors Group
Jet Propulsion Laboratory

Guillermo Rodriguez, Lead Technologist
Robotics and Mars Exploration Technology Programs
Jet Propulsion Laboratory

REFERENCES

1. Weisbin, C. R., Lavery, D. B., and G. Rodriguez, "Robots in Space: U. S. Missions and Technology Requirements into the Next Century," Journal on Autonomous Robots, Kluwer Publishers, Vol. 4, pp. 159-173, 1997.

2. Weisbin, C. R., "Robotics Technology for Planetary Missions," IEEE Robotics and Automation Magazine, Aug. 1998.

3. Krotkov, E., “Tactical Mobile Robotics,” DARPA Tech `97, 19th Systems and Technology Symposium, September 24, 1997.

4. Golombek, M. P., “The Mars Pathfinder Mission,” Scientific American, July 1998.

5. Schenker, P. S. et al, "Lightweight rovers for Mars science exploration and sample return," Intelligent Robotics and Computer Vision XVI, SPIE Proc. 3208, Pittsburgh, PA, Oct. 14-17, 1997.

6. Schenker, P. S. et al, "Dexterous robotic sampling for Mars in-situ science," Intelligent Robotics and Computer Vision XVI, SPIE Proc. 3208, Pittsburgh, PA, Oct. 14-17, 1997 (Invited, 16 pages).

7. Schenker, P. S. et al, "New planetary rovers for long range Mars science and sample return," Intelligent Robotics and Computer Vision XVII, SPIE Proc. 3522, Boston, MA, Nov. 1-5, 1998 (Invited, 14 pages).

8. Baumgartner, E. T., et al, "Sensor fused navigation and manipulation from a planetary rover," in Sensor Fusion and Decentralized Control in Robotic Systems (Eds., P. S. Schenker, G. T. McKee), SPIE Proc. 3523, November, 1998, Boston, MA;

9. Baumgartner, E. T. and S. B. Skaar, "An Autonomous Vision-Based Mobile Robot," IEEE Transactions on Automatic Control, Vol. 39, No. 3, pp. 493-502, March, 1994.

10. Yoder, Y. D., E. T. Baumgartner, and S. B. Skaar, "Initial Results in the Development of a Guidance System for a Powered Wheelchair," IEEE Transactions on Rehabilitation Engineering, Vol. 4, No. 3, pp. 143-151, September, 1996.

11. Hoffman, B., E. Baumgartner, P. Schenker, and T. Huntsberger, "Improved Rover State Estimation in Challenging Terrain", to appear in Autonomous Robots, February, 1999.

12. Olson, C. and L. Matthies, "Maximum Likelihood Rover Localization by Matching Range Maps." To appear in Proceedings of the International Conference on Robotics and Automation, 1998.

13. Laubach, S., J. Burdick, L. Matthies, "Autonomous Path-Planning for the Rocky7 Prototype Microrover." To appear in Proceedings of the International Conference on Robotics and Automation, 1998.

14. Volpe, R., J. Balaram, T. Ohm, R. Ivlev. "Rocky 7: A Next Generation Mars Rover Prototype." Journal of Advanced Robotics., 11(4), December 1997.

15. Volpe, R., "Navigation Results from Desert Field Tests of the Rocky 7 Mars Rover Prototype" International Journal of Robotics Research, Special Issue on Field and Service Robots. Submitted for publication.

16. Schenker, P. S. et al, "A composite manipulator utilizing rotary piezoelectric motors: new robotic technologies for Mars in-situ planetary science," SPIE Conference on Enabling Technologies: Smart Structures and Integrated Systems, Proc. SPIE SS97, San Diego, CA, March 3-6, 1997